Abstract
Most linear modern linear regulators use a PMOS architecture. This application note explains the key characteristics of a PMOS Low-Dropout Voltage Regulator (LDO) and the theory behind it.

1. Fundamentals
A voltage regulator is a constant voltage source that adjusts its internal resistance to any occurring changes of load resistance to provide a constant voltage at the regulator output. The internal resistance of a constant voltage source (Figure 1) must be significantly smaller than the external load resistor ($R_{IN} \ll R_L$) to ensure a constant output voltage over a certain range of load.

![Figure 1. Constant-Voltage Source](image1.png)

The output voltage of a voltage source under load condition is calculated with:

\[
V_O = V_{IN} \cdot \frac{R_L}{R_{IN} + R_L}
\]

Under the no-load condition ($R_L = \infty$), the open-circuit output voltage ($V_{OC}$) is the maximum possible output voltage, which is equal to the input voltage: $V_{OC} = V_{IN}$. As the load increases, the output voltage drops from its maximum value and introduces an output-voltage error, $E_{VO}$. This error is defined as the percentage difference between $V_{OC}$, the output voltage under no-load condition, and $V_O$, the output voltage under load condition:

\[
E_{VO} = \frac{V_{OC} - V_O}{V_{OC}}
\]

When replacing $V_{OC}$ with $V_{IN}$ and substituting $V_O$ with Equation 1, the output voltage error is expressed through the resistor ratio of $R_{IN}$ to $R_L$:

\[
E_{VO} = \frac{R_{IN}}{R_{IN} + R_L}
\]

A plot of the voltage error over a series of $R_L/R_{IN}$ ratios confirms that the output voltage error, $E_{VO}$, increases with decreasing load resistance $R_L$, as shown in Figure 2.

To minimize the error, we need a circuit that senses any occurring load changes and, using some kind of feedback, adjusts a variable internal resistor to keep a constant ratio of internal-resistance to load resistance, as described by Equation 4.
When the relationship described in Equation 4 is true, $R_{IN}$ must follow $R_L$ in a linear relation, as expressed by Equation 4. The corresponding equivalent circuit is shown in Figure 3.

An electronic circuit that achieves this relationship by adjusting the variable input resistance is basically a linear-voltage regulator (Figure 4). Its functional building blocks are discussed in the following sections.

1.1 Voltage Reference, $V_{REF}$

The voltage reference is the foundation of all regulators. This reference is of the band-gap-type, which has the ability to operate at low supply voltages while providing sufficient accuracy and thermal stability to meet the less-stringent performance requirements of regulators. Bandgap references typically have an initial error of 0.5% to 1.0% and a temperature coefficient of 25ppm/°C to 50ppm/°C.

1.2 Error Amplifier

The error amplifier senses a scaled-down version of the output, $V_P = V_O \cdot R_2/(R_1 + R_2)$, compares it against the reference voltage ($V_P = V_{REF}$), and adjusts $V_O$ using the series-pass element to the value required to drive the error signal ($V_{ERR} = V_P - V_{REF}$) as close as possible to zero. Setting $V_{REF} = V_P$ and solving for $V_O$ yields Equation 5:

\[
V_O = V_{REF} \cdot \left(1 + \frac{R_1}{R_2}\right)
\]

This calculation holds true only if $V_{IN}$ is sufficiently high to keep the error amplifier and the pass element from saturating.

1.3 Feedback Network

The feedback network scales $V_O$ to a value suitable for comparison against $V_{REF}$ by the error amplifier. Because $V_{REF}$ is fixed, the only way to program the value of $V_O$ is by adjusting the ratio $R_1 / R_2$.

1.4 Pass Element

The series-pass element boosts the output-current capability of the error amplifier to the higher levels required by the load. This process involves transferring large currents from the source, $V_{IN}$, to the load under the low-power supervision of the error amplifier. A suitable pass element to carry out this task is a PMOS enhancement FET.

A PMOS FET has the two p-islands for the source and the drain terminals embedded in an n-substrate (Figure 5). The substrate is connected to the source, which usually has the most positive potential. The drain receives the most negative potential.

As the PMOS name indicates, the device uses p-type conductivity, which is established by applying a voltage to the gate that is negative relative to the source. The holes, which are the minority carriers in the n-substrate, are attracted by the negative gate electrode. Moving towards the upper region between the two p-islands, the holes
now become free-charge carriers, establishing a p-conductive bridge between source and drain. This way, the conductivity of the bridge and the drain current $I_D$, are controlled by the gate-source voltage, $V_{GS}$.

Because this type of FET enhances its conductivity with increasing $V_{GS}$, it is called an enhancement or normally-off type (Figure 6).

### 2. Regulator Sequence

This section describes the regulation sequence when $R_L$ drops as shown in Figure 9. Figure 7 depicts how the regulation sequence described relates to the internal LDO blocks.

When the load resistance drops, the output voltage falls from $V_{O1}$ to $V_{O2}$, and the voltage across the pass element rises from $-V_{DS1}$ to $-V_{DS2}$. $V_P$ (the scaled-down version of $V_O$) falls significantly below $V_{REF}$ causing the gate-source voltage to jump from $-V_{GS1}$ to $-V_{GS2}$.

The PMOS FET now conducts harder, increasing the output current from $I_{O1}$ to $I_{O2}$. The output voltage and, by virtue of $V_p$, the error voltage starts to recover. The gate voltage increases gradually to $-V_{GS3}$, therefore causing the increased output current $I_{O3}$ to generate an output voltage $V_O$. When this output voltage is scaled down using $R_1$ and $R_2$, the result is a zero-error voltage $V_{ERR} = 0$.

The output characteristic shown in Figure 8 confirms the regulation sequence. When $R_L$ drops, the PMOS FET operating point jumps from $P_1$ to $P_2$ and then regulates to $P_3$. 
For a given quiescent point, P3, where the output voltage is stabilized (that is, \(V_{OUT}\) and \(V_{DS}\) are constant), the corresponding output current, \(I_{OUT3}\), is defined through Equation 6:

\[
I_{OUT3} = \frac{V_{DS}}{R_{IN}} = \frac{V_O}{R_L}
\]

Then, solving for \(R_{IN}\) yields:

\[
R_{IN} = R_L \cdot \frac{V_{DS}}{V_O}
\]

With \(k = V_{DS}/V_O\), Equation 7 provides the linear resistance relation required by a linear voltage regulator.

3. Revision History

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<thead>
<tr>
<th>Rev.</th>
<th>Date</th>
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<tbody>
<tr>
<td>1.00</td>
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